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Apparent dynamic stability of the southeast African coast despite sea level rise

Alan M. Smith, Simon C. Bundy and J. Andrew G. Cooper

ABSTRACT

The coast of southeast Africa is dominated by sandy beaches that tend to be confined within log-spiral or headland bound embayments. Investigations using serendipitous air imagery data set have been previously undertaken and conclusions drawn about the stability of the coast. We show that conclusions drawn from this data, with respect to the high water mark (HWM) position are fraught with errors, which include tidal state, pressure regime, beach slope, high-swell erosion, seasonal and multi-annual changes. We highlight and discuss these sources of error, together with their magnitudes. The most significant of these are the high-swell, seasonal and multi-annual variations. From case studies we show that the seasonal beach rotation and long-term beach width variation are responsible for tens of metres of unaccounted HWM variation, 30 to 50m is common, with maximums reaching 60 to 100 m. Overall the southeast African coastline appears to be in a state of long-term dynamic equilibrium. There is no evidence of any sea-level rise-forced transgression in the coastal sediment budget, despite sea-level rise (SLR). If such a signal is, in fact present, it is lost within the beach width variation. Some southeast African coastal reaches are suffering chronic erosion, but these are related to anthropogenic impacts. The extreme difficulty of placing a HWM, with any temporal validity on this coast precludes the routine use of the Bruun Rule. Although no transgressive signature is found, there is evidence of a decreasing coastal sand budget as a result of anthropogenic or natural climate change, or both. This decrease in the coastal sand volume is likely to result in increased future erosion.

Introduction

There is a general belief that global beaches are under threat due to sea level rise (SLR) and increased storminess (Guastella and Rossouw, 2013; Intergovernmental Panel Climate Change (IPCC), 2013). As early as 1985, Bird stated that at least 70% of the world's sandy beaches are eroding. Coastal erosion is often related to SLR (Leatherman, 1991; Zhang et al., 2004), and the Bruun Rule (Bruun, 1962) is frequently applied to predict the amount of coastline recession expected (Mather and Stretch, 2012), despite its lack of predictive power and false assumptions (e.g. maintenance of an equilibrium profile) (Cooper and Pilkey, 2004). While the Bruun Rule is retained for its instant solution, it has been solidly tweaked over the years and is no longer the simple tool it once was (Rosati et al., 2013). Extreme caution should be used when applying the Bruun Rule, unless the bathymetry, geomorphology and sedimentology can support its underlying assumptions.
The influence of rock outcrop, the presence of a substantial vegetated coastal dune cordon, a robust longshore drift, sedimentation rate, grain calibre and coastal engineering need to be considered in studies of shoreline processes. Pilkey et al. (2011) have noted that natural beaches are almost indestructible, except by human intervention. The controlling geology, sediment volume flux and texture, wave, wind and current action, together with longer term oceanic/atmospheric and climatic and tidal cycles must also play a role (Oost et al., 1993; Gratiot et al., 2008; Black et al., 2009; Smith et al., 2014a; Guastella and Smith, 2014).

The coastal literature generally agrees that the global sea level is rising (Bird, 2000; IPCC, 2013) although, the amount varies geographically and relative to other geological processes, such as isostatic rebound. A recent global study (Chen et al., 2014) has suggested that between 2005 and 2011 global SLR has decelerated by 44% to a value of 2.4 ± 0.54mm/yr. In contrast to this, Hay et al. (2015) contend that the value was 3.0 ± 0.7mm/yr between 1993 and 2010. From this it is evident that there is a general consensus that sea level is rising, although the amounts of SLR may be disputed (Kench et al., 2015).

KwaZulu-Natal Coastline

The southeast African coast borders the Indian Ocean (Figure 1). Its continental shelf is very narrow (12 to 47 km) (Bosman et al., 2007; Cawthra et al., 2010) when compared to the global average of 78 km (Shepard, 1963; Kennett, 1982). The southeast African shelf gradients vary from 2° to 8° (Cawthra et al., 2012). Inland the coast has a high freeboard (Orford et al., 2003) and a steep hinterland gradient (5°), 250km inland from Durban the topography reaches 3000 m.

The high freeboard means that high wave run-up cannot dissipate onshore and this results in an offshore-directed relaxant flow (Smith et al., 2010). The narrow and steep continental shelf reduces energy loss to friction consequently the coast is open to a strong wave energy regime. KwaZulu-Natal (KZN), a province of South Africa, is located on the southeast African coast (Figure 1). The KZN coast is remarkably straight (orientated roughly southwest–northeast) and measures some 560km in length. The southern coast (south of Durban) comprises mostly pocket beaches and small log-spiral bays. The central region (Durban to the Thukela River) is composed mostly of log-spiral bays and the north (beyond the Thukela River) is a mixture of linear beaches and logspiral Bays. sea cliff coastal reaches are relatively rare, but when present possess a well-defined shore platform. Beach reaches controlled by discordant geology are characterized by log-spiral bays. The KZN coast is microtidal-to-low mesotidal [highest astronomical tide (HAT) of 2.3 m: Durban and 2.5 m: Richards Bay].

Coarse-grained to pebbly, wave-dominated reflective beaches are the most common. A well-developed beach berm separates the intertidal beach from the backbeach. The latter is generally bounded landward by a steep dune cordon, often several tens of metres high. The longshore drift generally flows from south to north, driven by the prevailing wave climate (Cooper, 1991a, 1991b; van der Borch van Verwolde, 2004), but can reverse in the lee of headlands (Guastella and Smith, 2014).

Coastal erosion is common at known erosion hotspots (Smith et al., 2010, 2013) and activated by individual high-swells, seasonal wave climate variation (Smith et al., 2010; Guastella and Smith, 2014) and longer-term wave climate cycles (Smith et al., 2014a, 2014b). Coastal erosion is an integral part of the seasonal, coastal-cell beach rotation process (Short, 2002; Dolphin et al., 2011; Guastella and Smith, 2014), and results in large (tens of metres) seasonal changes in the high water mark (HWM) position on KZN coast.

The southeast African coast wave regime is robust with an average significant wave height for Durban of 1.65m (Corbella and Stretch, 2012a, 2012b), and it experiences occasional very high-swells such as the 2007 March Equinoctial (high swell, Hs = 8.5 m) event (Smith et al., 2007). Such events do not usually occur in isolation, but as components of high-swell groups (Smith et al., 2010; Loureiro et al., 2012). The 2007 March Equinoctial event is estimated to be a 1:35–61 year event (Corbella and Stretch, 2012a, 2012b), although simple historic occurrences suggests that the minimum return interval for a swell of this magnitude (or greater) is 15–20 years.

KZN coastal erosion is related to both the ±4.4 year lunar perigean subharmonic (LPS) and the 18.6 year lunar nodal cycle (LNC) (Smith et al., 2010, 2013, 2014a; Corbella and Stretch, 2012a, 2012b). The LNC appears to control the summer rainfall pattern in southern Africa (Malherbe et al., 2014) and thus also controls river runoff. No obvious correlation between coastal processes and El Niño southern oscillation (ENSO) have been noted (Guastella and Rossouw, 2013). However, recently Botes (2015) noted a link between KZN extreme floods and the Pacific Decadal Oscillation (±60 year cycle).

The sea-level at Durban, on the southeast African coast (Figure 1), is rising and is measured at 2.7mm/yr, between 1967 and 2006 (Mather et al., 2009). In contrast the National Oceanic and Atmospheric Administration (NOAA, 2016) data indicates that SLR for Durban is 1.23mm/yr (1990–2015). Sea-level has risen by more than 130m since the Last Glacial Maximum (Waelbroeck et al., 2002; Ramsay and Cooper, 2002; Green and Uken, 2005), excluding the mid-Holocene high stands (Davies, 1980; Cooper et al., 2013).

Analyses of historical shoreline change rely on available datasets, most commonly vertical aerial photography. In many cases the dates of the older airphoto flights are unknown. These impose limitations in deducing long-term rates of shoreline change (Dolan et al., 1978). Two attempts have been made to analyse the KZN coast line (Figure 1) using changes in the HWM position over time [Cooper, 1991a, 1991b, 1994 (published in three parts); Goble and Mackay, 2013). Both these studies have used the same 1937–1983 vertical, airborne coastal imagery dataset, although the latter have updated this to 2012. The HWM was identified on the coastal images by using the wet–dry contact, marked by a change in colour, generally assumed to represent the previous high tide line (Morton, 1974; Dolan et al., 1978). These studies take no account of seasonal variation, tidal status (including the spring tidal-cyle, the LNC and the LPS cycle, which strongly impact on tidal height and hence beach inundation), episodic high-wave events and other long-term climatic cycles (e.g. ENSO and the Pacific Decadal Oscillation) that may impact on the HWM position.

Omitting the affects of such cycles can have profound implications for the interpretation of long-term trends. For example, the omission of the LNC, which causes global sea-level to rise and fall by some 2.2cm over an 18.6 year cycle resulted in a SLR over-estimation for the coast of Holland (Baart et al., 2014).
No natural examples of permanent land loss, as the result of coastal transgression, are known from the southeast African coast. Intuitively, it seems reasonable that the coastline should be transgressive due to SLR, however analysis of the existing

HWM fluctuation data suggests that there has been as much recession as progradation between 1937 and 1983 (Cooper, 1991a, 1991b, 1994), whereas between 1937 and 2012 Goble and Mackay (2013) found that only a quarter of the stations used showed regression. This could suggest that transgression may be increasing. With a general SLR the lack of an observed general shoreline transgression requires explanation (Figure 2). Both previous studies (Cooper, 1991a, 1991b, 1994; Goble and Mackay, 2013) identify regressive sections of the coastline. For example a pronounced regression was noted immediately north of the Thukela River, (Cooper, 1991b; Green et al., 2013), the largest river in KZN, and also in the vicinity of the Richards Bay harbour inlet (Figures 1, 2). The former is due to riverine sediment input at a wave-dominated delta (Cooper, 1991a; Bosman et al., 2007) and the latter to coastal engineering. Other apparent regressive localities are not as easy to explain.

Many researchers do not appreciate the potential error in the extraction of HWMs from serendipitous air imagery. If the date and time of the flight is known, then errors such as: tidal state, pressure regime, beach slope and grain calibre, high-swell erosion, seasonal and long-term cycles can be accounted for on that date. However, this information is either not known or ignored. Here we critically examine the previous work in the light of new understanding concerning the HWM variation due to seasonal change and longer-term cyclicity (Smith et al., 2010, 2013, 2014a, 2014b; Corbella and Stretch, 2012a, 2012b; Guastella and Smith, 2014). These errors are discussed, analysed and conclusions drawn. Then we use case studies to illustrate the natural variation of the HWM envelope on the southeast African coast, so that these can be differentiated from genuine long-term changes driven by SLR. These case studies were chosen to illustrate the wide variation in HWM position. This research is augmented by extensive fieldwork, GoogleEarth and surfcam imagery.We compare our new data with previous studies which were reliant on the historic airphoto image database set and explore possible sources, and magnitude, of errors, in the establishment of historic HWMs.

Methods

This investigation was conceived to uncover the reason why the southeast African coast is not transgressive in the face of SLR. From time to time structures within the intertidal and subtidal zone are damaged, but this is a high wave-energy setting.

Structures in the supratidal zone and landward experience occasional damage, but in general this is simply repaired. No lessons are learned and it happens again. During the March Equinoctial high-swell of 2007 a house was lost at Ballito (Figure 1) and another badly damaged (Smith et al., 2007), but the dry land on which the destroyed house stood has since returned, and the badly damaged house has since been repaired. At other places reclaimed land comes repeatedly under marine attack. Beach managers generally do not realize the extreme beach width variation on the southeast African coast. This study investigates these large beach width variations on the KZN coast, southeast Africa.

The case studies used are:

1 Greater Durban Region (Figure 1): This draws on published data for the 2007 swell group impact (13 events). The year 2007 was a LPS peak year and followed 2006, the year of the LNC peak.
2 Nyoni, Rocks Beach, Amanzimtoti (Figure 1) for the time period: June (2006) to July (2007).
3 Chain Rocks Beach, Amanzimtoti (Figure 1). This period ranges from 10 October (2011: LPS peak year) and 6 March (2013: LPS trough year) spanning half an LPS tidal cycle (±4.4 year).
4 South Beach, Umdloti (Figure 1) during the bulk of a LPS tidal cycle from 10 March (2011: LPS peak year) to 19 July 2014 (2015 is an LPS peak year so spring tides were comparatively high).
5 Beachwood Mangroves Beach, Durban (Figure 1) over the time period of 1931 to 2015. The imagery used is for 2014 (nothing later available) but this was supported by fieldwork in 2015. This period more-or-less spans the last Pacific Decadal Oscillation cycle.

We tabulate our results and compare them with previous results and fully discuss the implications. Then we interrogate our data to ascertain whether any climate change or SLR signature is present and thoroughly discuss our results.

Results

The following errors were explored in the placement of the HWM position from imagery analysis.

HWM error due to disregarding tidal cyclicity

KZN is characterized by reflective beaches and has a microtidal-low mesotidal coastline. Consequently the intertidal zone is comparatively narrow. Insufficient attention has been given in previous studies to the dates and times of imagery capture (if known) due to its sporadic nature (flown in good weather when finances were available). In particular, the 28 day lunar tidal cycle variation has not been taken into account. Differences in elevation between the lowest annual neap high tide and the spring HAT is about 1m. This means that the width of the intertidal zone could be underestimated by up to 50%.

HWM error due to disregarding pressure variation

On a year-to-year basis atmospheric pressure may also exert an effect upon the state of tides, either suppressing or increasing tidal influence on the beach. The reverse atmospheric effect influences the tidal maxima attained in any given tidal period. Its effect is most evident in solar semi-diurnal tides (Lindzen and Chapman, 1969). Low pressure systems tend to raise sea levels and high pressure systems tend to lower them [Association of Australian Ports and Marine Authorities (AAPMA), 2005]. Barometric pressure causes an approximately 0.1m sea level drop per 10 hectopascal rise in pressure (Australian Meteorological Bureau, 2014). The effect of wind set up on tides is also well documented (De Cuevas et al., 2007).

HWM error due to disregarding the beach slope

The beach slope angle, especially on gently sloping coasts where the beach is wider, can introduce an error if the beach slope has changed significantly between surveys. If megacusping develops, as happens seasonally on this coast (Guastella and Smith, 2014), the beach slope error could become significant. A further point to be considered is the change in sediment calibre. This can occur seasonally due to the higher swell regime in winter (van der Borch van Verwolde, 2004) which forms coarser and steeper beaches. This may not change the location of the HWM but could change the position of the low water mark (LWM).

A study in the Durban hinterland catchment has shown that more than half the river sand is intercepted by dams or sand mining (Theron et al., 2008). Further, sand removal from coastward flowing rivers and streams has the potential to change the sediment calibre. KZN beaches are fed by steep, short-headed, braided systems and usually comprise very-coarse, granular or pebbly sand. Industrial sand mining preferentially removes the 0.5 to 1.0mm fraction, causing the mean beach sand grain calibre to increase and the beach profile to steepen in response.

Similarly, the sterilization of the dune cordons for urban development and agriculture removes sand from the system. In addition, plaster sand mining preferentially removes sand in the 0.125 to 0.250mm size range which will also act to increase the beach sand calibre and potentially increase the beach slope. If this is the case, then the LWM may have transgressed, although this possibility needs to be further researched before it can be assessed.

HWM error due to disregarding the seasonal beach width changes

Seasonal horizontal changes on KZN beaches during the austral winter of 2007 varied from 5 to 100 m (Smith et al., 2010). This extreme seasonal erosion was triggered by a storm swell group. The largest (Hs = 8.5 m) struck on the March Equinox and was followed by two (Hs = 5m and 4.5 m) further events (Smith et al., 2010). The previous authors noted that the long-term envelope of HWM mobility, as given by Cooper (1991a, 1991b, 1994, was in some instances similar to the austral winter 2007 seasonal variation, but in other cases the 2007 erosion greatly exceeded it. The 2007 high swell values used by Smith et al. (2010) were obtained during post-storm field visits and data may not have been captured at the maximum erosion.

Most of the erosion hotspot (EHS) locations on the KZN coast are confined within headland-bound embayments and logspiral bays. These sandy beaches are known for their high seasonal variation, 30 to 50m HWM variation being common (Smith et al., 2010; Guastella and Smith, 2014). EHS sand losses during the stormy winter of 2007 were made good within two years (Corbella and Stretch, 2012a, 2012b). This suggests that HWM position analyses (Cooper, 1991a, 1991b, 1994; Goble and Mackay, 2013) may be picking up seasonal to annual variations rather than genuine long-term trends.

HWM error due to disregarding very high-swell events

Very high-swell events (Hs ≥ 8m) are known to produce significant coastal erosion (Jeukes, 1976; Smith et al., 2007). These have been recorded from 1934 (dated image); 1953 (credible witness), 1966, 1984 and 2007 (Jeukes, 1976; van der Borch van Verwolde, 2004; Smith et al., 2007, 2014a). In the Durban area the March 2007 coastal erosion varied from 5 to 60m (Loureiro et al., 2012). The effects of these, sometimes dramatic events, are partially repaired by natural coastal processes, within months (Smith et al., 2010), and completely within two years, as in the March 2007 event case (Corbella and Stretch, 2012a, 2012b). Normal high-swells may cause elevated water levels and coastal erosion but this can be repaired in days to weeks (Smith et al., 2013).

The March Equinoctial 2007 high-swell had a wave run-up of 4 to 11m above mean sea level (a.m.s.l.) (Mather, 2007) and produced catastrophic erosion. This event is probably somewhere between a 15 and 35 year event, indicating that it was a significant but not an extreme event. In addition, normal wave run-up on any given day will be modified by wave period, wave propagation direction (Smith et al., 2014c), degree of beach deflation and the state of the offshore bars. Thus wave run-up following a high-swell event will provide a HWM indicator that can in no way be seen as having the equivalent physical inshore state as any other comparative day of any other year.

HWM error due to disregarding long-term cycles

HWM position analysis is further complicated by the fact that erosion is more prevalent during certain parts of long-term cycles, something that is rarely if ever considered. Recent research suggests that erosion due to high-swell events can be expected during the 18.6 year LNC peak (Gratiot et al., 2008; Smith et al., 2010) and during the ±4.4 year LPS cycle peak (Corbella and Stretch, 2012a, 2012b; Smith et al., 2013). Smith et al. (2014a) showed that the peak of the 18 year South African Summer Rainfall cycle, or Dyer-Tyson Cycle (Malherbe et al., 2014), correlates with the trough of the 18.6 year LNC. Rainfall ultimately controls the amount of sand that reaches the coast and regulates the amount of coastal sand buffer, and consequently the position of the HWM.

As the Summer Rainfall Precipitation cycle and LNC are out of phase, higher sand input coincides with the lower tides of the LNC trough. Conversely, the lower fluvial sand input corresponds with the higher tides of the LNC peak (Smith et al., 2014a). On the KZN coastline, the LPS influence becomes more noticeable during times of low precipitation/river flow, especially around the LNC peak (Smith et al., 2014a). Thus knowing and understanding this relationship and its timing is critical when coastal imagery is being assessed for the HWM. These cycles are not well known by beach managers and hence are inadvertently lumped into long-term coastal or climate change. From the Cooper (1991a, 1991b, 1994 database, it can be seen that many stations show a change of HWM movement over time. This often manifests as a positive HWM change, followed by a negative HWM change, often of a similar magnitude. This could be the coastal response to natural multi-year cycles (Smith et al., 2014a) which have not been taken into account.

Case studies

Greater Durban area

An aerial survey of the greater Durban coastline (Figure 1) was flown on 17 March 2007, a little over 24 hours later it experienced a 5 to 60m HWM retreat due to the impact of the March Equinox (2007) high-swell event (Smith et al., 2007; Loureiro et al., 2014). The next survey was flown in June (2007), by which time a strong seasonal winter erosion event, complicated by catastrophic seasonal beach rotation was well underway (Smith et al., 2010). The difference between the two events (high-swell and austral winter erosion) is not generally appreciated and consequently the effects of the March Equinoctial (2007) storm are confused with the austral winter erosion of the same year. Not all KZN beaches experienced erosion during both events (Smith et al., 2010). Coastal erosion from the 2007 high-swell event repaired within two years (Corbella and Stretch, 2012a, 2012b) if the coast had been flown two years later all evidence of the 2007 erosion event would have gone.

Nyoni Rocks, Amanzimtoti, Durban

This beach underwent minor erosion during the March Equinoctial (2007) high-swell event, but experienced 100m of coastal recession during the following austral winter (Figure 3). If it had not been for an engineering intervention another 50 m and possibly as much as 100 m, would have been lost.

Chain Rocks, Amanzimtoti, Durban

In this example the HWM advanced by 50m (Figure 4) between 10 October 2011 and 6 March 2013, a period with no major high-swell events. The envelope of mobility of this bay is zero (Cooper, 1991b). The long-term change may be zero but the seasonal variation is 40 to 50 m. The year 2011 coincided with the LPS (±4.4 year cycle) peak and the expected coastal erosion (Corbella and Stretch, 2012a, 2012b; Smith et al., 2013) was evident. In contrast, the progradational situation in 2013 was near the peak of the Dyer-Tyson Rainfall Cycle, a time when rainfall is expected to be greater (Tyson, 1986; Malherbe et al., 2014), consequently river runoff was higher and the amount of sediment reaching (and buffering) the coast was greater.

South Beach, Umdloti

The change in HWM here is quite marked. On 10 March 2011 the high tide beach was very narrow. In contrast three years later there was 50m of high tide beach in the central part of the Umdloti Beach on 19 July 2014 (Figure 5). The long-term

(1937–1983) envelope of mobility for this beach is estimated at 15m (Cooper, 1991a), indicating that such episodes had not previously been recorded from aerial photography. The peak of the LPS cycle was in 2011, and was characterized by strong coastal erosion (Smith et al., 2013), consequently a gain in beach width was to be expected.

Beachwood mangroves, uMgeni River mouth, Durban

Beachwood, located on the coast north of the uMgeni River, has a photogramic record going back to 1931 (Figure 6). In the 1931 image a shooting range can be seen and this is still visible in 1970 images where the city infrastructure was welldeveloped and good coordinates could be obtained (29° 48′ 14.5"S; 31° 02′ 33.6"E and 29° 48′ 17.0"S; 31° 02′ 34.1"E).

Two snap shots in time as to where the shooting range was and would have been (it was lost to the sea in the 1987 erosion) are shown (Figure 6). Evidence presented (Cooper, 1991a) shows that the Beachwood HWM retreated by 150 m between 1937 and 1983. The comparison offered here suffers from the same inadequacies as the earlier work but seems to suggest that although there is a marked HWM variation, for almost a century there is no long-term trend.

The Inanda Dam was built on the uMgeni River in 1989 to serve Durban (Figure 1). Prior to dam closure the uMgeni River supplied an average of 810 to 1300 × 10^3 tonnes of sand, whereas in the post-dam era the downstream tributaries provided between 72 and 119 × 10^3 tonnes (Garland and Moleko, 2000). Even including this large-scale engineering the HWM has remained fairly constant (Figure 6).

Discussion

From Table I, it is evident that most of the errors are much smaller than the high-swell, seasonal, inter-annual and port engineering HWM position variation but should not be ignored (Table II). The port engineering HWM is well constrained in location. High-swell, seasonal and intra-annual HWM variation are very large and beg the question as to whether an average HWM can be estimated (Table II).

These errors are not cumulative. Those accrued from tidal variation, beach slope and general mapping vary from ±3 to 20m (Table I) and are small when compared to the seasonal and multi-annual HWM variation. Port engineering gives the highest variation, but is easier to constrain because of its context (Table I). Seasonal, multi-annual and high swell variation are clearly the most important variables, but constraining them is difficult as the observational baseline is so short (Table II). The gauged high-swell history dates back to 1984, prior to this it is reliant on newspaper and historical accounts. In the case of coastal erosion events, the documented records only go back to 2007. Prior to this it is essentially anecdotal. The early 1930s were known as a time of severe coastal erosion in the Durban area. This is usually blamed on the interruption of the longshore drift sand supply due to dredging (and offshore dumping) down longshore drift of the Durban harbour breakwater (Barnett, 1999), although the harbour inlet was already in existence prior to this. Erosion hindcasts, using the LNC (Smith et al., 2014a), indicate that the early 1930s should have experienced severe coastal erosion, a fact apparently borne out by the historic evidence. Further there is growing evidence that the Pacific Decadal Oscillation influences precipitation in KZN (Botes, 2015). The Pacific Decadal Oscillation peaked in the early 1940s and again in the mid 1990s.

The available imagery used to investigate the KZN coast spans the period 1931 to present, although the earlier images are spaced eight to 22 years apart and thus the dataset lacks fine-tuning. Further, aerial photography is done in good weather and consequently often seasonally biased. The conclusions from earlier studies (Cooper 1991a, 1991b, 1994; Goble and Mackay, 2013) are strongly dependent on when the imagery was captured. Both (the three Cooper references are part of a single survey) these studies commenced in 1937 which was near the peak of the 18 year Dyer-Tyson summer rainfall precipitation cycle. During this time rivers would have been flowing strongly to the coast, resulting in a high sediment supply. The Cooper (1991a, 1991b, 1994 study ended in 1983, which was at the peak of the Great Natal Drought, a time when the city of Durban (population two million then) instituted severe water rationing, and the coast would have been sediment starved. The Goble and Mackay (2013) study commenced in 1937 and ended in 2012, near the peak of the Dyer-Tyson summer rainfall precipitation cycle. Cooper (1991a, 1991b, 1994 did not identify long-term coastal trends but quantified the relative HWM envelopes of change. These values contain both seasonal and multi-annual components (Table II) and should probably be considered as minimums. In contrast, Goble and MacKay (2013) use the apparent HWM changes to assert that the coastline is dominantly transgressive. Table II shows that there is significant HWM variation, although the seasonal and multi-annual HWM variation may be similar to the HWM envelope of mobility. These values should be adjusted by ±3 to 20m (Table I).

Recently, continuous daily video records became available for certain beaches (Guastella and Smith, 2014; Smith et al., 2014b). This new data source has highlighted the dynamism of beach geomorphology in the very-short-term (hours to days) and over a seasonal timescale. In the absence of continuous data it is generally assumed that the arbitrary collection of time-capsuled imagery can be used for long-term coastal change analysis (Fikir et al., 2014), but new understanding of the influence of episodic events and cyclic processes call this into question, particularly on bedrock-framed coasts such as that of southeast Africa.

The Durban and Richards Bay harbour entrance breakwaters are interfering with longshore drift and consequently the worst erosion is down longshore drift of these inlets (Figure 1). Sand nourishment schemes are in place but are inadequate. There are no reports of ongoing transgressive coastal problems on the southeast African coast (outside of urban or urbaninfluenced areas). All reports concern high-swell events – and seasonally reversing EHSs, usually at times of unusually high tides (Smith et al., 2007, 2010, 2013). These EHSs are subject to reversal under natural repair (Smith et al., 2010; Corbella and Stretch, 2012a, 2012b). Exceptions are within heavily urbanized, and often structurally defended, beaches. Empirical evidence indicates that the KZN coastline is stable and those few coastal reaches that are genuinely regressive, are associated with welded beach ridges down-longshore drift of river mouths (Cooper, 1991b; Green et al., 2013).

Despite SLR (Mather et al., 2009; NOAA, 2016) the southeast African coast HWM shows an apparent dynamic stability in position over the past 7–8 decades. Evidence points to a multidecadal erosion/deposition cycle (Smith et al., 2014a) resulting in a HWM advance and retreat. The large-scale loss of beach property expected under continuing SLR has not taken place. This suggests that, in the long-term, fluvial input is presently balancing out the anticipated effects of SLR.

Using the IPCC (1998) Bruun Rule of thumb (1 cm SLR produces 1m coastal retreat) gives 10m (1.23mmyr. 1) to 17m (2.7mmyr. 1) of coastal retreat since 1931. These numbers are comparable with some of the lesser errors (Table I) but small compared to the values shown in Table II. Perhaps the influence of SLR is being lost within the short-to-medium term HWM changes. Against this uncertain backdrop it is impossible to assign an average HWM position. The Bruun Rule is routinely practiced on the southeast African coast (Mather and Stretch, 2012). This practice has become increasingly challenged worldwide (Cooper and Pilkey, 2004), and in view of the evidence presented here should be treated with extreme caution on this coast. If no knowledge of a coastal reach exists the Bruun Rule can be used as a first approximation but it should be reconsidered when better information becomes available. Regardless, the value of the Bruun Rule calculation must be questioned as it is almost impossible to establish a meaningful HWM against which this calculation can be done.

Climate change has to be evaluated as a contributor to the unexpected stability of the southeast African coastline. Seventy percent of South Africa experienced a significant increase in the intensity of rainfall events between 1931–1960 and 1961–1990. Further increasing probabilities of extreme rainfall is predicted by the General Circulation Models (Joubert et al., 1996; Joubert, 1997; Mason and Joubert, 1997). Although rainfall does not appear to be increasing overall (Botes, 2015), it is being delivered in more intense bursts (Mason et al., 1999). This might result in more fluvial floods and hence higher water velocities, which could deliver more sediment to the coast and continue to buffer it. In contrast to this theory, evidence from the Durban harbour dredging activity does not support this (Figure 7).

The longshore drift sand moves south to north and consequently accumulates to the south of the southern Durban harbour breakwater. This sand has to be removed by dredging to keep the harbour inlet clear. The annual amounts removed show a cyclic pattern that may follow the LNC (Smith et al., 2014a) but which is decreasing overall (Figure 7). As the sea level is known to be rising, its impact must be masked by the seasonal and multi-annual HWM cyclicity. The decreasing sediment volume reaching the coast (as shown by the longshore drift proxy) contradicts the climate change hydrology (see Mason et al., 1999) but supports the work of Theron et al. (2008). Houston (2015, and references cited therein) has discussed examples of landward movement of marine sediment resulting in coastline accretion during SLR. The concept of beach rotation on the southeast African coast (Guastella and Smith, 2014) clearly supports shoreward and offshore sand movement during the same swell. Unfortunately deposition is seldom seen as a problem and hence receives less attention than coastal erosion. After the March Equinoctial high-swell (2007), statements were made that it was unlikely that the coastal erosion lost sand would come back (Smith et al., 2007), although most beaches had returned to their normal state by mid 2008 (Smith et al., 2010) and all within two years (Corbella and Stretch, 2012a, 2012b). June 2008 was a period of high floods on the central and lower KZN coast which may have introduced the sediment that repaired the beaches. There is no doubt that large sediment volumes were moving offshore at depths of at least 20m during the 2007 high-swell event (Smith et al., 2010). Further, the build-up of sediment landward of the persistent offshore aeolianite reef (60 m) (Flemming, 1981) is probably due to historical high-swell return flows on this coast. Clearly sediment leaves the coast, but the onshore sediment movement required for natural repair needs to be assessed. The difficulty of placing a HWM that has any temporal validity precludes the use of the Bruun Rule on this coast. However, within urban areas where engineering control of the HWM exists the Bruun Rule may still prove useful.

Conclusion

The coast of southeast Africa is dominated by sandy beaches, mostly confined within log-spiral or headland-bound embayments. The beaches within these settings are highly dynamic. Several investigations using the air imagery data set have been previously undertaken and conclusions drawn. We show that this dataset contains errors, the most significant of which are the high-swell, seasonal and multi-annual HWM variations. The southeast African coastline shows no evidence of an overall long-term transgression within the period of record. Large seasonal and inter-annual HWM fluctuations do occur but overall the coastline appears to be dynamically stable. For this coastal dynamic stability to exist, sediment input must be balanced by sediment output. If SLR-induced transgression is ongoing the signal is lost within the large seasonal and multiannual beach width fluctuations. The only long-term changes noted are within urbanized and coastal reaches which have undergone extensive land-use changes. At present the southeast African coast is insufficiently well understood to assign any sort of average HWM position precluding the general use of the Bruun Rule on this coast.

Although no climate change signature is found, there is evidence of a decreasing coastal sand budget. This may reflect an anthropogenic effect or climate change or both. A decrease in the coastal sand volume is likely to result in increased future erosion.

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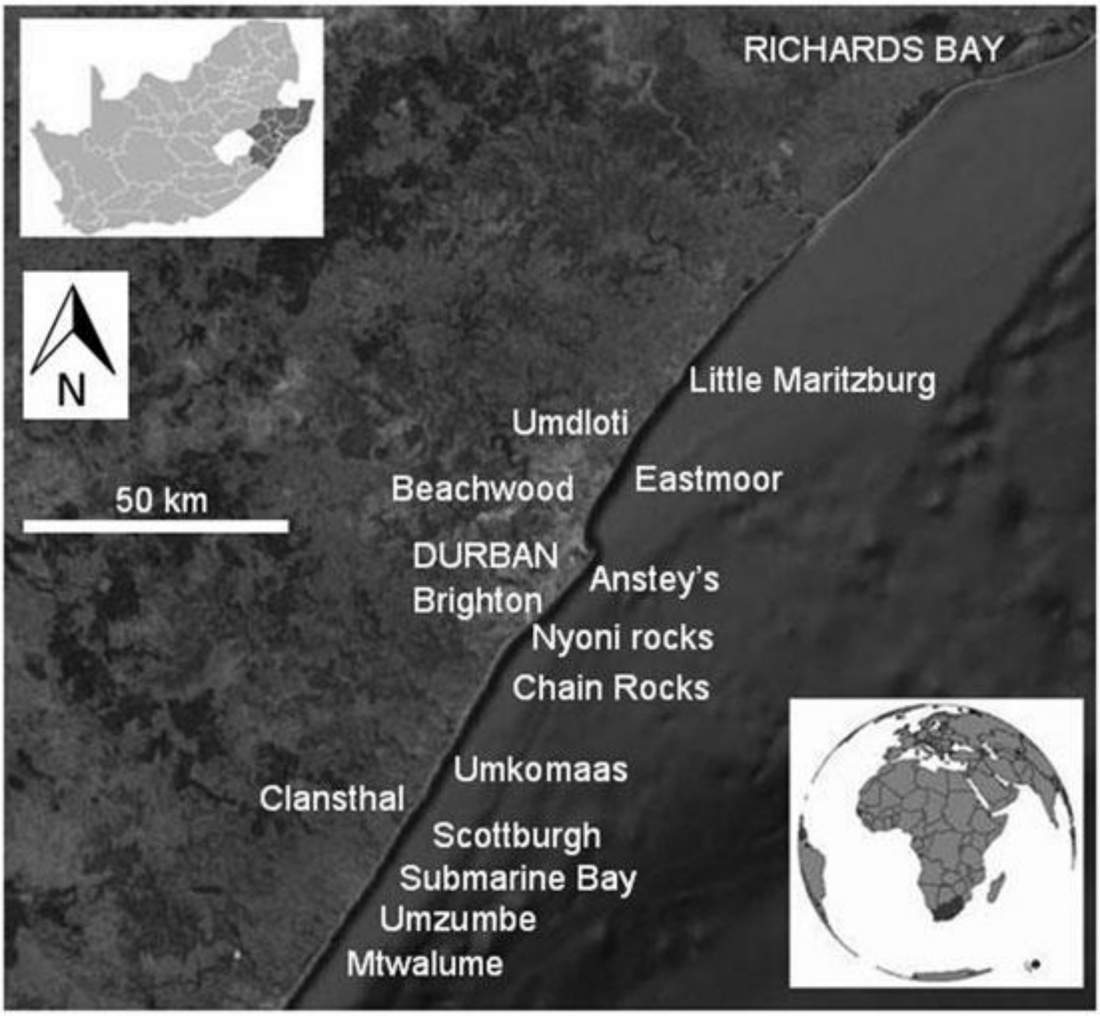

Figure 1. Location map showing the main cities of Durban, Richards Bay and all other locations mentioned in the text. Inset bottom right shows the global perspective of the southeast African coastline and the inset, top left, the regional location of KwaZulu-Natal Province.

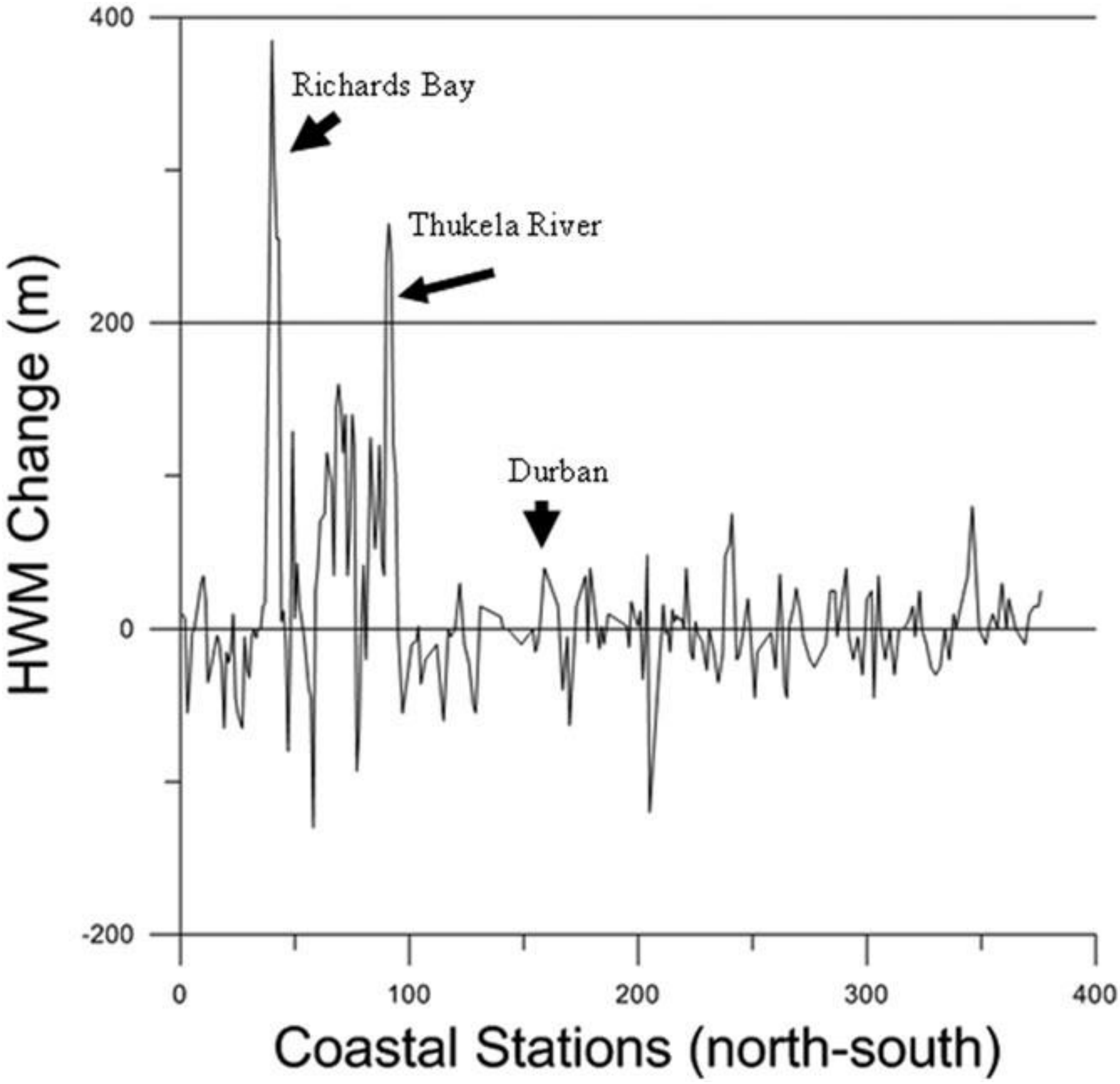

Figure 2. Cooper (1991a, 1991b, 1994 divided the coast into 1.5 km slices however for this figure the trend line shown has been drawn at 7.5 km intervals. From this data it can be seen that, south of the Thukela River, there was about the same amount of apparent transgression as regression between 1937 and 1983. However north of the Thukela River and in the Richards Bay area, the coast is clearly regressive. This is due to northward asymmetry of the wave-dominated Thukela Delta, and to the large-scale port engineering required to construct the port of Richards Bay (completed in 1974). Coastal recession of 500m has been recorded at this location.

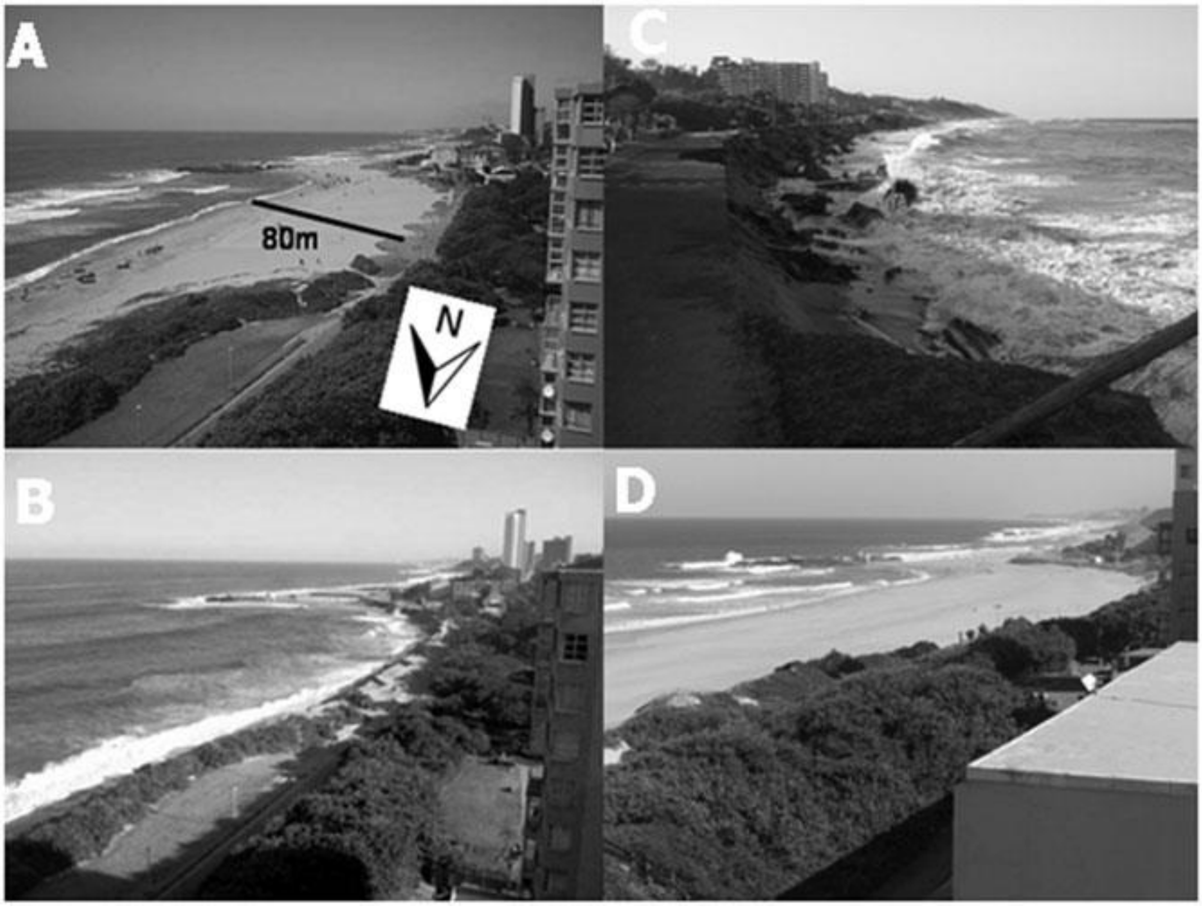

Figure 3. Between June 2006 (A) and July 2007 (B) the Nyoni Rocks high water mark (HWM) moved 100 m. A close up of the 2007 megarip current erosion (C) is shown. The coast had returned to normal within two years, the situation in April 2010 is shown for comparison (D). Prior to this event the HWM envelope was considered to be 38m (Cooper 1991a).

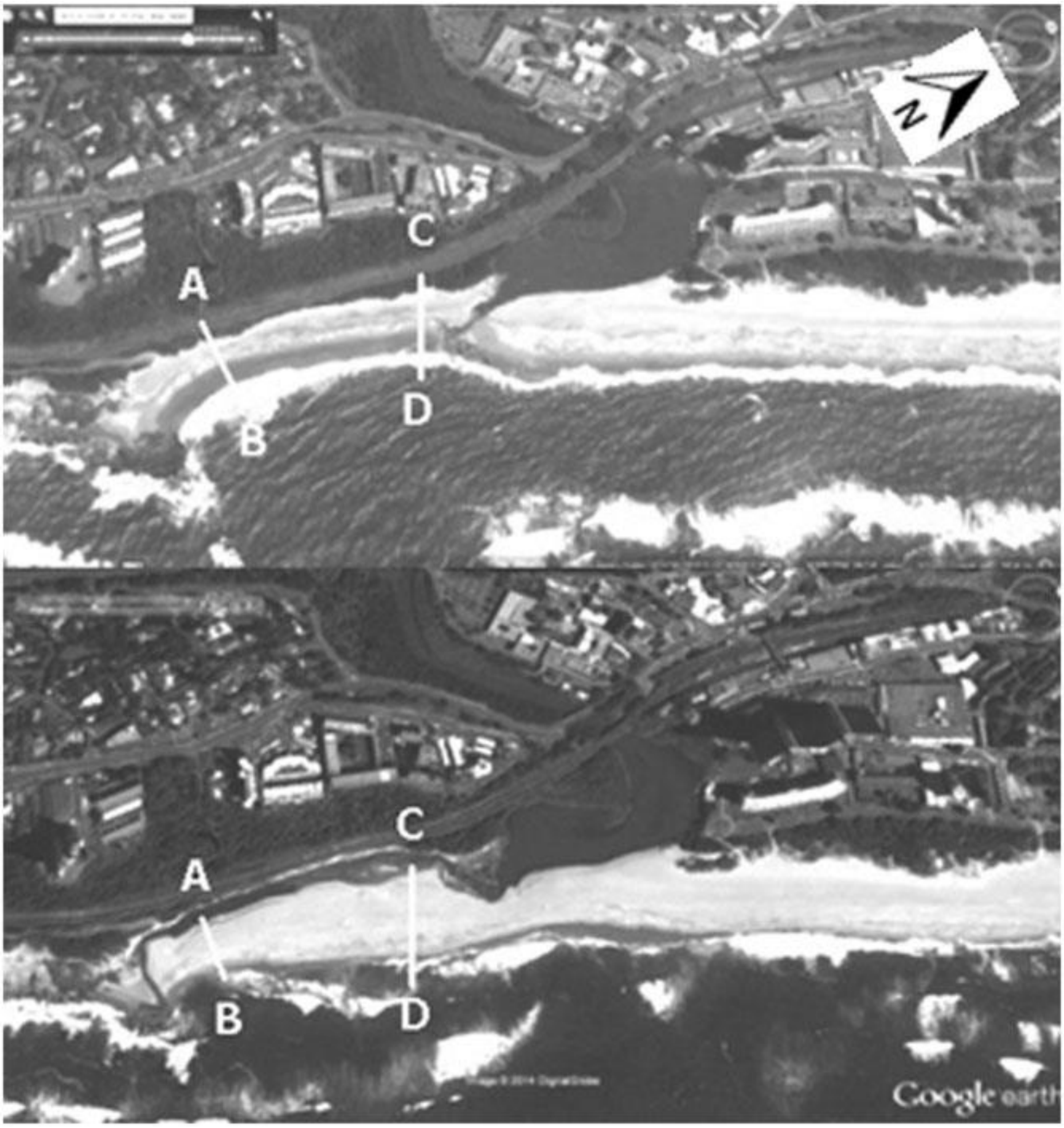

Figure 4. Chain Rocks beach. Here the marked beach width variation between 10 October 2011 and 6 March 2013 can be seen.

Figure 5. Umdloti Beach. In the top image (10 March 2011) there was no beach at high tide, whereas in the lower image (19 July 2014) there is 50m of beach.

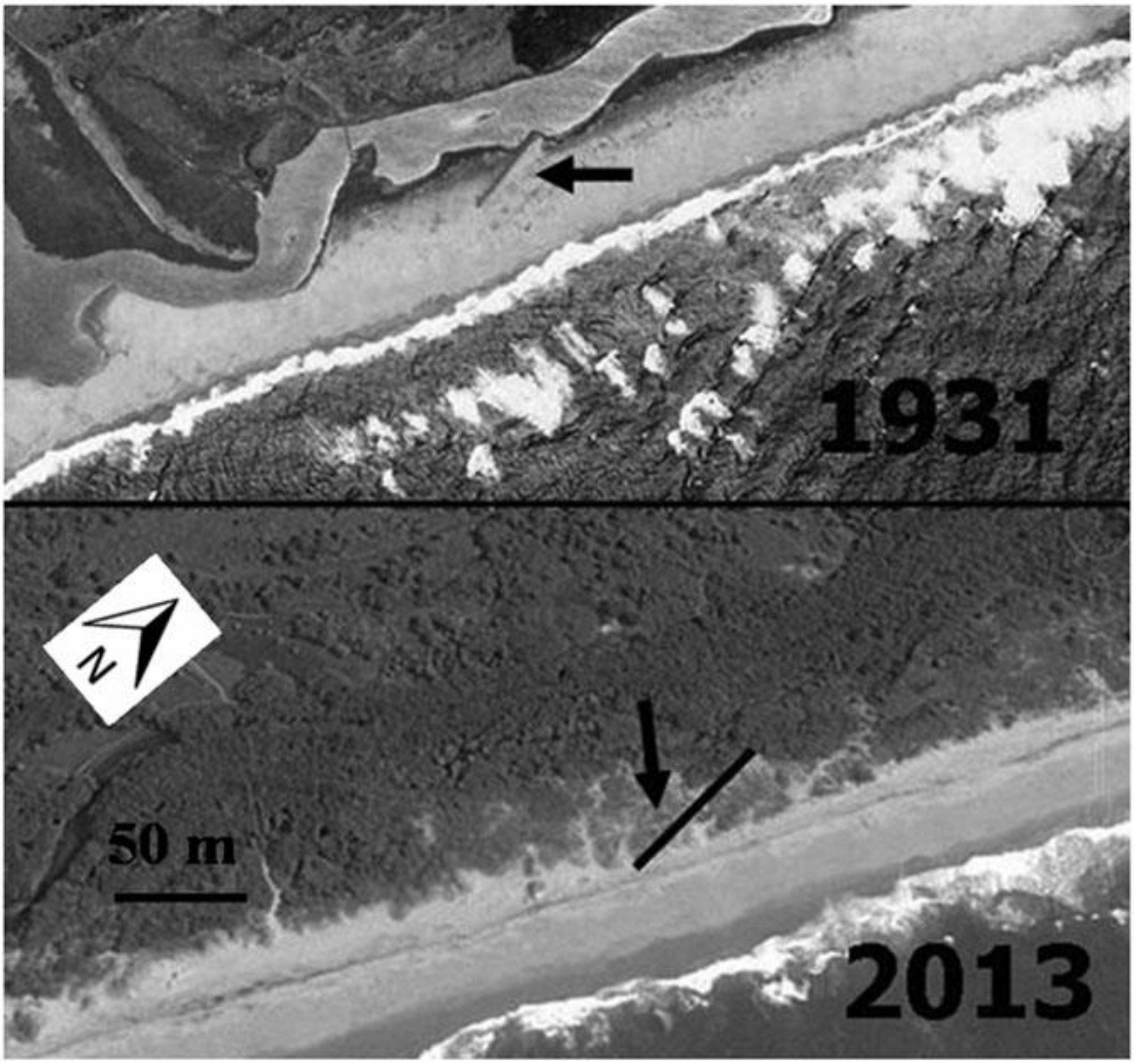

Figure 6. Comparison of the Shooting Range location between 1931 and 2013. This comparison can be extended to 2015 but the subsequent GoogleEarth images are less clear. The location of the Shooting Range has not been dry land for the entire 84 years (lost to coastal erosion in 1987) but the ‘lost’ coastline has returned. This comparison is even more interesting as the uMgeni River (immediately to the left in both images) was dammed in 1989.

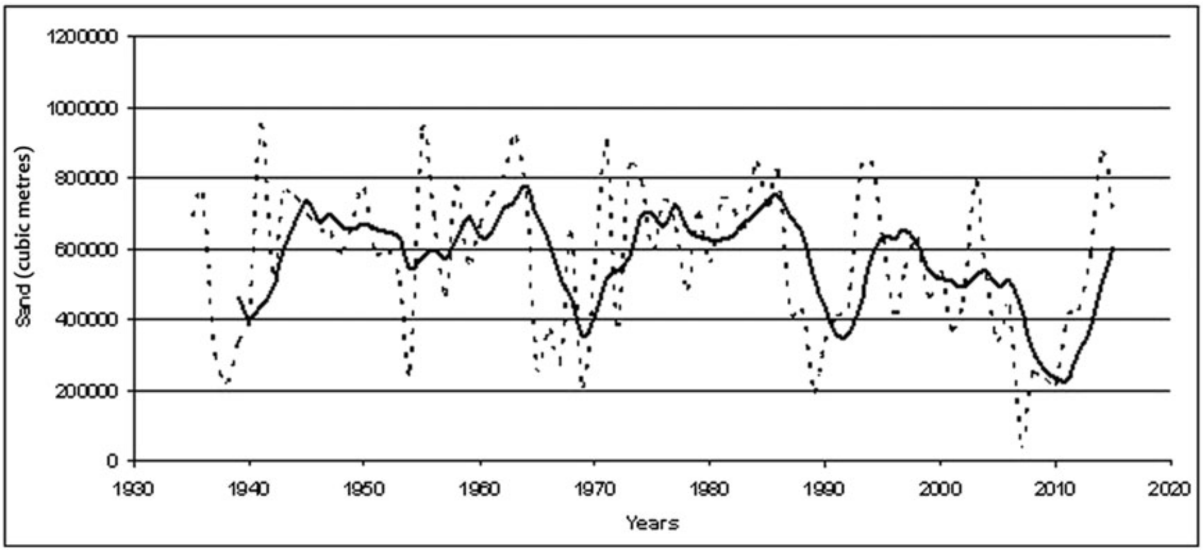

Figure 7. This graph represents the annual sand volumes removed from the Durban harbour dredge site (dotted line, solid line is five-year running mean). Although the record starts at 1890, the modern dredging era only really began in the late 1930s, thus early data is not reliable and omitted.

Error source	Amount	Remarks	Source
Beach slope	3 to 5 m	Within seasonal envelope	This paper
Tidal	1.4 to 20 m	Within seasonal envelope	This paper
Seasonal	5 to 100 m	Very large	Smith *et al*. (2010)
Multi-annual cycle	10 to 50 m	Probably exceeds seasonality	This paper
High-swell	0 to 60 m	Data only exists for March 2007 event	Smith *et al*. (2007, 2010
Port engineering	Up to 500 m		Cooper (1991b)
Pixel size	Variable		Garel *et al*. (2015)

Table I. Possible errors introduced by the use of coastal imagery

Location	March 2007 high-swell (m)	2007 Winter erosion (m)	Multi-annual (post 2008–2015) (m)	Envelope of mobility (1937–1983)
Richards Bay	30	30	20	25
Little Martizburg	50	25	20	40
Umdloti	16	30	50	40
Eastmoor Cresent	60	30	30	48
Ansteys Beach	30	30	10	18
Brighton Beach	30	35	15	55
Nyoni Rocks	?	100	30	38
Chain Rocks	?	30	50	0
Umkomaas	10	65	30	65
Clansthal	?	30	30	53
Scottburgh	50	50	35	52
Submarine Bay	?	75	35	57
Umzumbe	?	40	20	75
Mtwalume	?	40	40	55

Table 2. High water mark (HWM) changes recorded from the KwaZulu-Natal (KZN) coast (Cooper, 1991a, 1991b, 1994; Smith et al., 2007, 2010; Loureiro et al., 2012; This study).